

Impact of Train Type Heterogeneity on Single-Track Railway Capacity

Mark H. Dingler, Yung-Cheng (Rex) Lai, and Christopher P. L. Barkan

North American railroads are experiencing rapid growth in traffic demand and increasingly need to expand capacity to accommodate it. Efficient planning of new capacity requires understanding how the mixture of traffic interacts to affect capacity. Different train types can have substantially different operating characteristics, including maximum speed, power-to-ton ratio, and dispatching priority. Heterogeneity in the mix of characteristics of different train types creates greater delays than are created if traffic is homogeneous. Train dispatching simulation software was used to analyze the effect of various combinations of intermodal, unit, manifest, and passenger trains on a hypothetical, signalized, single-track line with characteristics typical of a North American railroad subdivision. Analyses included the influence on delay by various traffic and train characteristics. As has been shown by previous investigators, heterogeneity increases delay, but different types of heterogeneity had differing effects, which has implications for capacity planning. This paper attempts to provide a better understanding of the impacts of various aspects of train type heterogeneity to enable more effective planning and efficient rail operations. The results also suggest certain operating strategies that may reduce the delays caused by train type heterogeneity.

North American freight railroads are experiencing rapid growth in demand for their services and are increasingly experiencing capacity constraints. Between 2000 and 2006 the revenue ton-miles of U.S. railroads increased by more than 21% (1) and long-term growth is expected to continue. AASHTO predicts that the demand for freight rail services will increase 84% based on ton-miles by 2035 (2), creating the need to add more trains, increase their capacity, or both. Meanwhile Amtrak, VIA Rail, and commuter rail operations are expanding, placing further demand on the rail network. This growth, coupled with increased profitability since deregulation in 1980, has led to considerable investment in renewal and expansion of railroad infrastructure (3, 4); however, these investments are capital intensive. Efficient planning and financing of new capacity to meet demand requires understanding how expanded operations affect capacity (5).

A key factor that affects rail capacity is the interaction of different train types. Heterogeneity in train characteristics causes greater delays than corresponding homogeneity in train characteristics would. In

North America, intermodal, manifest, unit, and local trains may all share trackage. Some lines also have intercity passenger trains, and in metropolitan regions, commuter trains. Each of these train types can have considerably different characteristics, and even trains of the same class may have varying weights and lengths. This heterogeneity has a substantial effect on rail line capacity (6, 7).

Previous work has investigated some of the factors and effects of heterogeneous traffic on European and North American networks. Vromans et al. (8) studied the Dutch rail network and the heterogeneity of its various passenger services in order to homogenize the timetable to increase reliability. Landex et al. (9) also analyzed the Dutch rail system, but focused on the importance of line segment length in determining capacity with heterogeneous traffic. Abril et al. (10) conducted a comprehensive capacity study using Spanish rail lines. They considered trains operating at two speeds, "normal" and 50% of normal, on single- and double-track lines.

Others have looked at the impact of heterogeneity on the North American network. Bronzini and Clarke (11) used a single-track simulation model to compare the delay-volume curves of different mixtures of intermodal and unit trains. Harrod (12) modeled traffic using mathematical integer programming. He considered the differing impact of faster and slower nonconforming trains and found that the slower the nonconforming train, the greater the impact on the network. Gorman (13) used actual traffic data from Burlington Northern Santa Fe in an attempt to statistically estimate delay. He found that the most useful measures of train speed heterogeneity for predicting congestion delay are meets, passes, and overtakes. In this paper the authors describe research in which simulation modeling was used to extend this work by considering heterogeneity in several different parameters believed to affect capacity.

Dispatching simulation software was used to conduct quantitative analyses of the impact of heterogeneity among the principal train types operated on the North American railroad network. The authors evaluated the effects of various combinations of three different types of freight trains and one type of passenger train with different percentages of each train type on a signalized, single-track route. Delay was used as the principal metric to assess impact on capacity under different scenarios. The objective of this work is to provide insight into which aspects of traffic heterogeneity have the greatest impact on delay and develop a preliminary assessment of the potential economic impact on a typical rail line.

METHODOLOGY

There are a variety of factors that influence rail capacity and different metrics to measure it. Both operating and infrastructure characteristics influence capacity. Major factors include average and variability in operating speed, traffic volume, stability, terminal efficiency, and

M. H. Dingler, Railroad Engineering Program, B-118 Newmark Civil Engineering Laboratory, and C. P. L. Barkan, 1203 Newmark Civil Engineering Laboratory, Department of Civil and Environmental Engineering, University of Illinois at Urbana-Champaign, 205 North Mathews Avenue, Urbana, IL 61801. Y.-C. Lai, Department of Civil Engineering, National Taiwan University, Room 313, Civil Engineering Building, Number 1, Roosevelt Road, Section 4, Taipei, Taiwan, 10617. Corresponding author: M. H. Dingler, dingler2@illinois.edu.

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heterogeneity in various train characteristics. These factors are inter-related with, and further influenced by, infrastructure characteristics such as siding length and spacing, crossover spacing, number of tracks, signal and traffic control system, grade, and curvature. Consequently it can be difficult to precisely determine the available capacity of a particular route, and there will often not be a single correct answer. Further complicating matters, there are also a number of measures used to calculate capacity. Each of these metrics is useful for looking at a different aspect of railroad operations, but they are not easily convertible among each other. These measures include velocity, volume, tonnage, and delay.

In this paper the authors focus on the effect of heterogeneity in train characteristics on capacity and use average delay of all traffic on a line as the principal metric of comparison. Delay is defined as the difference between the minimum run time, or unopposed running time, and the actual run time to traverse the route, including the time spent stopped for meets and passes, along with the time for braking and to accelerate from stops. There has been some discussion about the use of delay as a metric of capacity (14). However, for the types of comparisons and circumstances addressed in this study, delay is a generally satisfactory measure and is used throughout this paper.

**Dispatch Simulation Software:
Rail Traffic Controller**

The authors used Rail Traffic Controller (RTC) from Berkeley Simulation Software for the analyses. RTC is a sophisticated software program designed to realistically simulate both freight and passenger operations over a railroad network (15, 16). Using infrastructure and traffic inputs specified by the user, the software resolves multitrain conflicts in the same manner as an actual railroad dispatcher. RTC was used because its flexibility permits rapid evaluation of a variety of different scenarios, and because of its widespread acceptance and use by the North American railroad industry.

Representative Rail Line

Specific characteristics of individual rail lines are unique, and route characteristics influence the study of railroad operations. For this research the authors developed a hypothetical rail line intended to represent the characteristics of a typical North American single-track mainline subdivision with the following attributes:

- 124 mi long;
- 10 mi between control points;
- 8,000-ft signaled sidings with #24 powered turnouts;
- 2.5-mi signal spacing;

- Three-block, four-aspect signaling; and
- 0% grade and curvature.

Although the attributes are somewhat idealized, the purpose is to provide a consistent basis for relative comparison of different scenarios of interest in this research under a reasonably realistic set of operating conditions. However, there is no intent to imply that the results presented here represent absolute predictive measurements for a particular set of conditions.

IMPACT OF TRAIN TYPE HETEROGENEITY

Four different train types with characteristics corresponding to typical intermodal, unit, manifest, and passenger trains were used to quantify the effects of heterogeneity. These train types are also reasonably representative of several other types of trains operating on the North American network. For example, auto trains will often have similar characteristics to intermodal trains and unit grain trains are similar to unit coal trains. Local switchers and commuter trains, which have completely different characteristics due to their frequent stops, were not included in this analysis.

The TRB Workshop on Railroad Capacity and Corridor Planning in 2002 provided typical weights, lengths, and horsepower-to-trailing-ton ratios for various train types. The authors used this information as the principal basis for the physical characteristics of the four train types used in this analysis (Table 1). The nonphysical characteristic of each train is the priority assigned to it by the dispatcher. When two trains meet, priority is one factor the dispatcher will take under consideration when determining how to resolve the conflict. Generally dispatchers will try to minimize the total cost of delay (15), meaning that the lower-value, lower-priority trains will enter the siding. By law, Amtrak passenger trains are to be given priority over freight traffic (17). Therefore, these trains were given the highest priority in the simulations. Of the freight trains considered, intermodal trains were assigned the highest priority, followed by manifests, and unit trains were assigned the lowest.

What is important in these analyses are the characteristics these trains represent, not the train types themselves. For example, intermodal trains represent freight trains with the highest maximum speed, power-to-ton ratios, and dispatching priorities, whereas unit trains represent those with the lowest speeds, power-to-ton ratios, and dispatching priorities. For simplicity, the trains will be referred to by these names for the remainder of the paper.

Delay-Volume Relationship

To understand the relationship between delay and volume better, the authors first conducted simulations that provided baseline delay-

TABLE 1 Train Characteristics Used in Simulations

Intermodal	Unit	Manifest	Passenger
90 cars	115 cars	70 cars	10 coaches
6,300 ft	6,325 ft	4,550 ft	850 ft
8,100 tons	16,445 tons	7,700 tons	610 tons
2.12 hp/trailing ton	0.78 hp/trailing ton	1.12 hp/trailing ton	6.96 hp/trailing ton
4 SD70 4,300-hp locomotives	3 SD70 4,300-hp locomotives	2 SD70 4,300-hp locomotives	1 P42-DC 4,250-hp locomotive
Maximum speed: 70 mph	Maximum speed: 50 mph	Maximum speed: 60 mph	Maximum speed: 79 mph

NOTE: hp = horsepower.

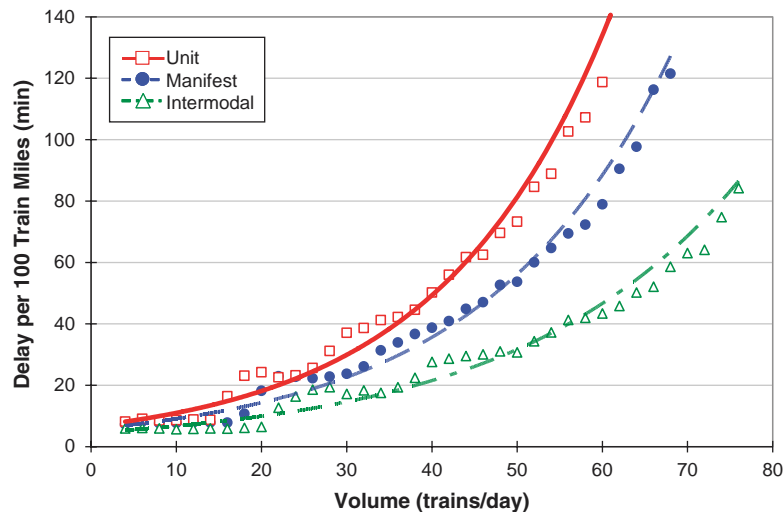


FIGURE 1 Delay-volume graph with trend lines.

volume results using homogeneous traffic consisting of each of the freight trains considered in this study (Figure 1). Trains were systematically added in pairs and evenly spaced temporally in each direction over a 24-h period.

On a single-track line the effect of additional trains on delay is not linear. Instead, the relationship between train volume and delay is exponential, with each train type and train mix (11, 18) having its own particular functional relationship. These curves provide a baseline for comparison of delay when there is a mixture of train types. The threshold for service quality acceptability will vary among different operators or customers, so there is no single level of delay that can be categorized as satisfactory. Consequentially, one cannot necessarily infer capacity directly from these curves because greater tolerance of delay will permit more traffic to traverse the same infrastructure. What is pertinent in the analyses is the difference in delay between these baseline conditions and the various experimental scenarios in which the heterogeneity of one or more of the parameters of interest is altered.

Assessment of Train Type Heterogeneity

There is considerable heterogeneity in freight traffic in the North American rail network. The percentage of different train types and heterogeneity in train characteristics in terms of different maximum speeds, power-to-ton ratios, and dispatching priorities all contribute to cause additional delays as compared with homogeneous traffic. To understand better the effect of each of these characteristics, the authors ran a series of simulations with various traffic and train configurations. For each configuration a series of 10 simulations was performed with the departure time of each train randomized over a 20-min interval, 10 min before or after the scheduled time for that train.

With purely homogeneous traffic, delays are entirely due to meets. With heterogeneous traffic, delays are also caused by conflicts that occur as a result of differences in train characteristics, some of which also increase the frequency and duration of meets. Additional sources of delay with heterogeneous traffic include

- Train delayed by a slower train,
- Train delayed by a train with slower acceleration,

- Trains experience longer meets waiting for higher-priority trains,
- Train delayed waiting for another train to pass, and
- Trains experience more meets due to lower average speed, which can be caused by lower speed, lower power, lower priority, or all three factors.

At each traffic volume each type of train will experience different delay depending on its characteristics. Each combination of traffic volume and train type mix will have an associated amount of delay. As the total traffic and percentage of each train type changes, the delay due to heterogeneity will also change. Therefore, the authors used the difference between the delay for the particular mixed traffic scenario, compared with the hypothetical delay that would occur for the same traffic mix in the absence of any of the heterogeneity-caused sources of delay.

Impact of Traffic Characteristics on Train Type Heterogeneity

Three parameters were tested to understand better their effect on delay: volume, percentage of each train type, and the combination of train types (Figure 2). Three pairwise combinations of freight train types were tested: intermodal and manifest, intermodal and unit, and manifest and unit. For each of these combinations, four traffic volumes were considered: 28, 34, 40, and 46 trains per day. These are theoretical volumes and are not intended to represent practical, sustained operation. Therefore the results will be more characteristic of the spacing between the trains than the actual volume. The mix of trains was incrementally altered by varying the ratio of each train type. At each traffic volume level, the percentage of each train type was varied from 0% to 100%. For all scenarios, the ratios and traffic pattern were the same for trains traveling in both directions.

Several trends with respect to volume, percent heterogeneity, and train types are evident. There was a strong correlation between traffic volume and extra delay due to heterogeneity. As traffic volume increased, the delay from heterogeneity increased exponentially (Figure 2a). There are two consequences of increased volume on the single track line that was simulated: more meets and shorter headways. Both of these are magnified by the different characteristics of the traffic.

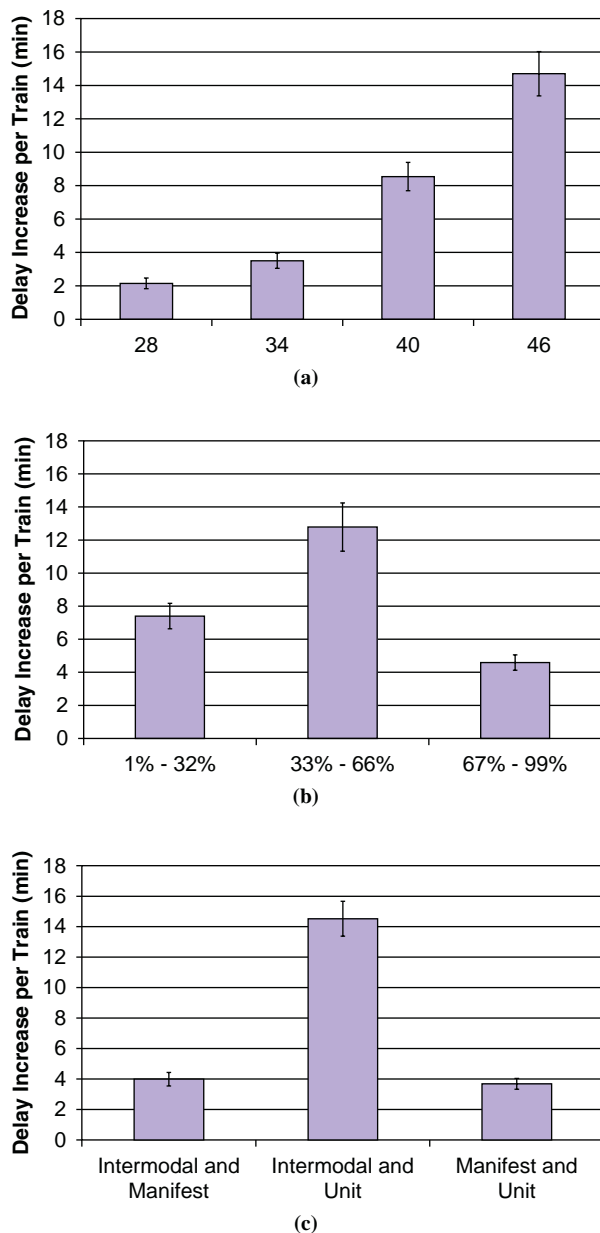


FIGURE 2 Additional delay in minutes per day, with 95% confidence interval due to heterogeneity sorted by (a) volume, (b) percent heterogeneity, and (c) train types.

The percentage of different train types also affects delay, with the greatest delay occurring when heterogeneity is highest (33% to 66%) (Figure 2b). This result was expected because there are more opportunities for conflicts. The two groups with less heterogeneity (the first and last thirds) both resulted in less delay than the middle third; however, they differed from one another because of differences in characteristics specific to train type.

The last traffic characteristic considered is the pairwise combination of train types (Figure 2c). The particular types of trains had a significant impact on the amount of delay created by their interaction. The combination with the greatest delay was intermodal and unit. This combination of trains had the largest difference in speeds, power-to-ton ratio, and priorities and resulted in more than three times as much delay compared with the other two pairwise combinations.

Impact of Train Characteristics on Train Type Heterogeneity

Although the effects of volume, percent heterogeneity, and train type were evident, the specific factors causing the increased delay were less clear. Further experiments were conducted with additional scenarios to investigate the sensitivity of delay to speed, power, and priority in order to clarify the influence of these train characteristics on delay. In these analyses, the authors used the scenario with the greatest delay, the mix of intermodal and unit trains at 46 trains per day, and then varied the specific characteristic to be tested.

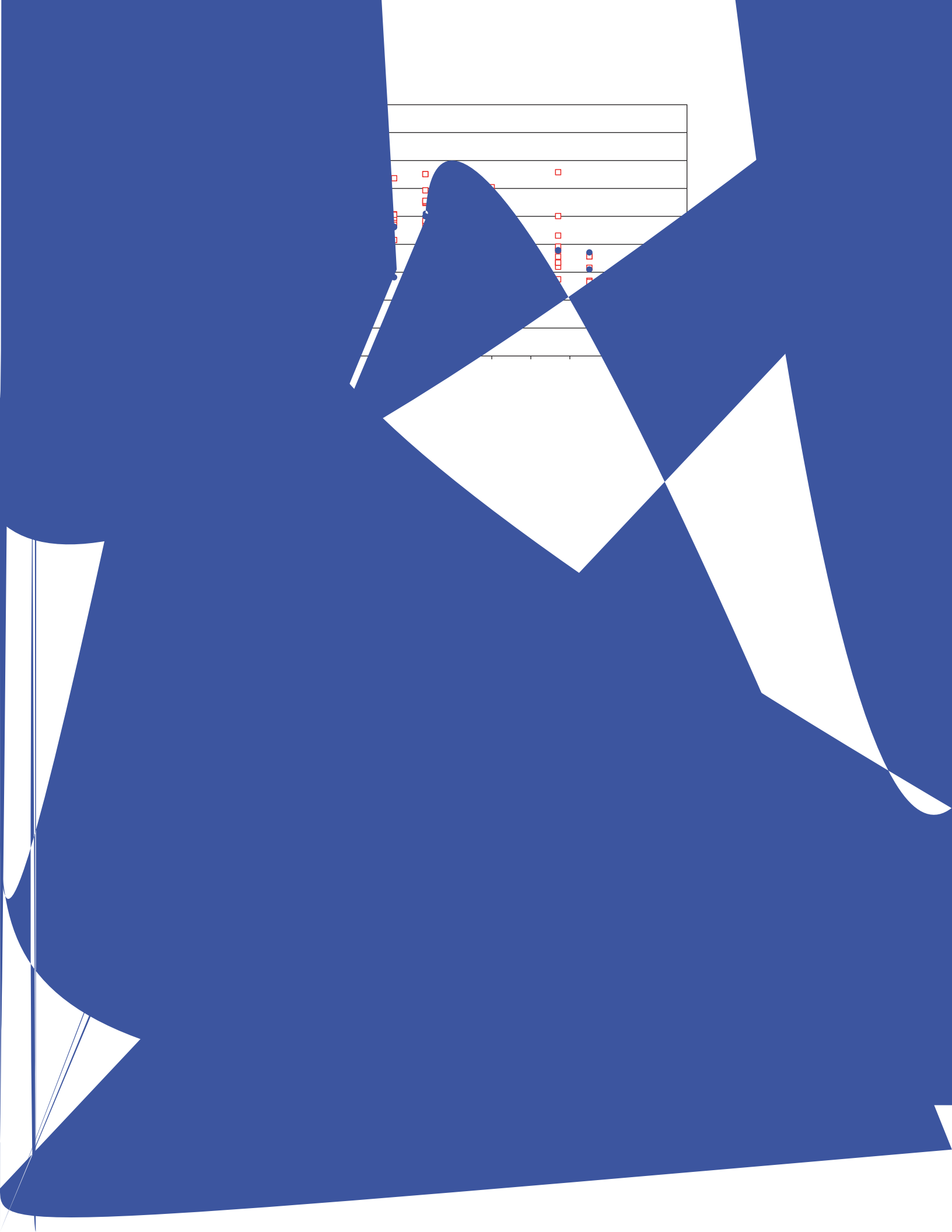
Heterogeneity in Speed To test the influence of heterogeneous speed on delay, the maximum speed of the intermodal traffic was reduced from 70 mph, to 60 mph and 50 mph, while all other parameters were held constant (Figure 3). This change reduced the speed difference among the train types, thereby making them more homogeneous, and reduced delay. When trains travel at different speeds, both the faster and the slower trains may be delayed. The faster train will be delayed when it overtakes a slower train and must slow to maintain a safe headway until it reaches a siding and can pass. The slower train will be delayed if it must enter a siding to wait for the faster train to pass.

Homogeneous speeds therefore lead to fewer delays on all traffic. However, when unit trains made up most of the traffic, there was little change in the average speed of traffic, even when the maximum allowable speed of intermodal trains was reduced. The slower speeds of the unit trains prevented the faster intermodal trains from ever reaching their top speed. Therefore, reducing their maximum speed had little effect on the observed run time. Instead, the reduction in delay was due to a change in the baseline condition. The reduction in maximum speed increased minimum run time; therefore, the difference in delay between the homogeneous and heterogeneous scenarios was also reduced.

On single track, frequent meets at higher traffic volumes means that trains may be unable to reach their top speed before braking for another meet. Greater homogeneity in speed will reduce train delay but may not have much effect if trains are already traveling at less than maximum speed because of congestion, heterogeneity, or both.

Heterogeneity in Power-to-Ton Ratio To test the influence of power-to-trailing-ton ratio, the effect of adding one locomotive to both intermodal and unit trains was analyzed (Figure 4). Increasing the power on trains reduces the time lost accelerating after stops, which has been found to be an important factor affecting delay (13). In these simulations delay was reduced for both train types, but the effect was greater for unit trains compared with intermodal. The incremental effect of the extra locomotive in reducing this form of heterogeneity was greater for the lower-powered unit trains. The presence of the lower-powered trains and the capacity they use while accelerating is the proximate cause of their impact on delay.

Heterogeneity in Priority The last characteristic considered was the dispatching priority assigned to trains. Intermodal trains with their higher-value merchandise and greater customer demand for fast, reliable service are typically given higher priority by railroad dispatchers. The baseline scenario in which intermodal trains were always given higher priority was compared with one in which both train types were given equal priority (Figure 5). In the baseline scenario there was a significant impact from the increased mix of traffic, but when individual train type priorities were removed, there



was little delay due to heterogeneity despite the other differences in train type characteristics. Dispatching priority appeared to have a much greater impact on delay than speed or power.

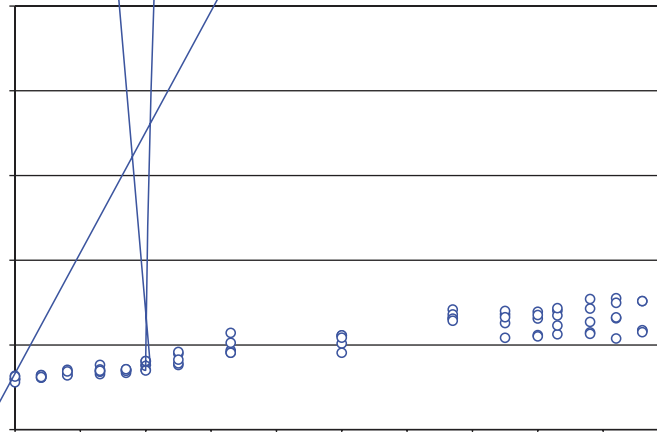
To investigate further the effect of priority on train type heterogeneity, the delay to each type of train was individually examined (Figure 6). When differential train priority was removed, the delay to each train type was similar (Figure 6a). The increase in delay due to different priorities (Figure 5) is not the result of an increase in delay of all trains. Only the lower-priority, unit trains experience the extra delay, with a minor decrease in delay for the higher-priority intermodal trains (Figure 6b).

Delay due to priority is not only dependent on the type of train but also the percentage of each train type. The increased delay of unit trains is greatest when the traffic is predominately intermodal; the few unit trains experience an increase in delay of more than 500%. However, when the traffic is predominately unit trains, with a few intermodal trains, equalizing priorities permits a nearly 50% decrease in delay. Priority is given to decrease the delay and increase the service

quality for the higher-valued freight. However, this assignment of priority significantly increases the delay for the lower-priority traffic, causing a higher average delay of traffic.

Cost of Heterogeneity

There are two basic types of cost due to heterogeneity: delay cost and opportunity cost. Delay cost represents the additional locomotives and rolling stock that are needed due to the delay, and the extra fuel and labor costs that accrue. It is calculated by summing four components: unproductive locomotive cost, unproductive rolling stock cost, idling fuel cost, and crew cost (19). This calculation provides an estimate of the cost for each hour a train is in service. A recent estimate of train delay cost was approximately \$213 per train hour (19), although the authors have heard higher estimates from railroads. With a mixture of half intermodal and half unit train traffic at 46 trains per day, the cost of the extra delay due to heterogeneity is



(a)

estimated at more than \$2.46 million per year for the hypothetical line analyzed. Although this estimate is based on the particular characteristics and scenarios considered in this paper, it provides some idea of the magnitude of the cost of heterogeneity.

Another way to consider the financial impact of heterogeneity is the opportunity cost that results from trains that cannot be operated. This metric would apply in the case of lines operating at or near capacity. The traffic volumes of heterogeneous traffic and homogeneous traffic at the same delay levels were compared, and the difference was considered the opportunity cost. With homogeneous intermodal traffic at a volume of 46 trains per day, the total delay is 30 min per 100 train miles. If the traffic is an equal mix of intermodal and unit trains at the same volume, delay increases 290%, to 87 min. At that delay level, if the traffic were homogeneous intermodal trains, the theoretical capacity would be 76 intermodal trains per day. The lost capacity is therefore 30 intermodal trains, or using the same method, six unit trains. Considered another way, if a railroad is currently operating 76 intermodal trains per day and wants to run 23 unit trains, 53 intermodal trains must be removed to run them. For each unit train added, 2.3 intermodal trains must be replaced. There is a direct trade-off for each train of the different type added. This trade-off is greater when trains are added that are not the same as the predominate type on a route.

Effect of Passenger Trains on Heterogeneity and Delay

So far the only heterogeneity considered is between different types of freight trains. Adding passenger trains to a freight-only line (or vice versa) adds considerable new heterogeneity because the pertinent characteristics of passenger trains are even more different than the variations among freight trains. Passenger trains have higher maximum speeds, power-to-ton ratios, and dispatching priorities than freight trains. This adds substantial heterogeneity to the train traffic operating on a route, creating even greater delays.

When passenger trains are added to a route, they are typically an addition to the freight traffic. Therefore, in these analyses, passenger trains were added to base volumes of freight. The authors used base freight train volumes of 32, 36, 40, and 44 trains per day composed of a mix of 80% manifest and 20% intermodal trains spaced evenly throughout the day. Pairs of passenger trains, up to four in each direction, for a total of eight, were added to this baseline freight traffic. The schedule was adjusted to preserve even temporal spacing between freight trains and the added passenger trains. The passenger trains had no scheduled stops in the simulations. If stops were considered, the delays would be greater, especially if the stops occupied the mainline.

To analyze the impact of passenger traffic on a predominately freight traffic line, the delay of the freight and passenger trains were considered separately (Figure 7). The delay to the passenger trains is unaffected by both traffic volume and the number of passenger trains being operated. During a meet, the higher-priority train is less likely to have to stop, meaning that independent of volume, the train will have similar delays and only stop when it meets a train of the same priority. When the volume of these high-priority trains is a small percentage of the total, as with passenger traffic on a predominately freight line, such meets are uncommon.

The delay of freight traffic is dependent on the volume of trains and number of passenger trains being operated. The freight traffic has a lower dispatching priority than passenger traffic. Therefore, when passenger traffic is increased, freight trains will experience more

meets and resulting delays. When multiple scenarios with the same volume are compared, in every case the scenario with the greater number of passenger trains has more delay. For instance, at the volume of 40 trains per day, three scenarios were considered: 40 freight trains with zero passenger trains, 36 freight trains with four passenger trains, and 32 freight trains with eight passenger trains. The scenarios with more passenger trains have greater delays, even though the total number of trains on the line is the same. Additional passenger trains cause greater delays than the same number of freight trains.

The delays of freight traffic also show an incremental effect of each added passenger train. In general the effect of each pair of trains is linear, with the addition of the fourth pair of passenger trains causing as much incremental delay as the first pair. If freight traffic is held constant, each passenger train will meet the same number of freight trains as the other passenger trains, suggesting that when estimating the delay of additional passenger traffic on a line, the delays created by current passenger traffic will be similar to the incremental delay created by the additional traffic.

DISCUSSION OF RESULTS

This assessment of heterogeneity provides insight into its impact on freight and passenger train traffic. A mixture of train types causes more delay than a comparable number of trains of similar characteristics. Consequently, disproportionately more time is required for trains to traverse the route, reducing its capacity. A change in the factors that influence heterogeneity can increase or decrease the traffic delay. Understanding each of these factors is necessary for efficient operations and planning.

The opportunity cost of each train is greatest when the train type added is the minority of current traffic. When planners are considering additional traffic, the types of trains is as important as how many when considering the impact on capacity. Volume should not be the sole measure of capacity. This work has shown even at a constant volume, traffic can experience very different delays, depending on the type of trains. A route may be operating at capacity at a variety of volumes, depending on the traffic mix.

Passenger trains are another source of heterogeneity on some freight lines. When passenger trains, with their higher priorities and speeds, are added to baseline freight schedules, the impact is greater than if the same numbers of freight trains are added. This additional effect needs to be considered when additional passenger trains are proposed for a route. These trains not only take up train slots that would otherwise be used by freight, but create additional delay for freight traffic as well.

Although traffic characteristics are difficult to change, the characteristics of the trains may be more flexible. In this paper, speed, power, and priority were considered, and changing each of these could result in reduced heterogeneity and consequent delay. Increased speeds may not be feasible for some trains; additional locomotives will generally require additional capital and operating expense; and removing priorities will incur some additional costs because of the increased travel times of the highest-priority trains. The cost-effectiveness and acceptability of each of these changes should be analyzed and compared with other options such as infrastructure expansion when a railroad is considering capacity expansion projects.

Finally, it should be emphasized that the results here represent general relationships based on idealized conditions on a hypothetical rail line. As such, they are intended to provide insight on the relative importance of different factors thought to affect delay, not

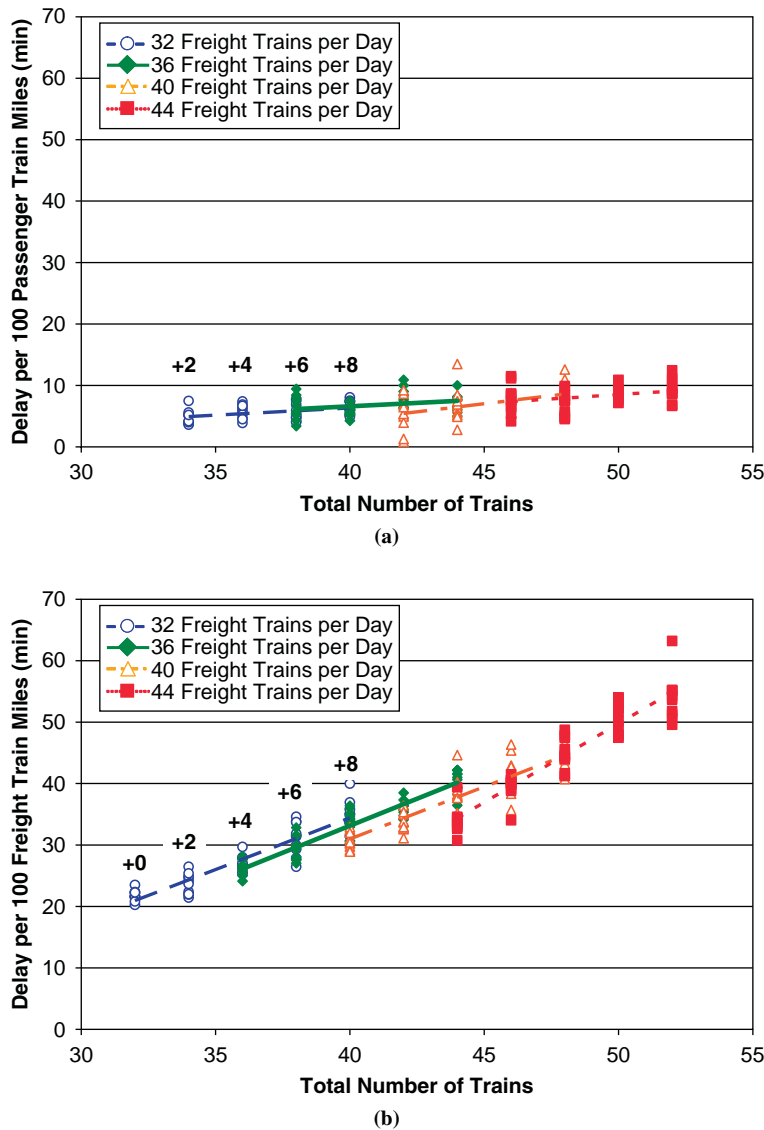


FIGURE 7 Delay versus number of trains for (a) passenger and (b) freight trains (figures indicate the number of additional passenger trains in each scenario).

absolute measures of capacity under the conditions described. Specific information about a particular infrastructure configuration and mixture of traffic would require a detailed study using appropriate data specific to the conditions being studied. The methods described in this paper could be adapted for such an analysis, and this work provides insight regarding what type of information is needed and likely to be important in such a study.

CONCLUSIONS

There is increasing demand for both freight and passenger rail transport in North America, and considerable capital is being invested in new infrastructure. Investing this capital efficiently requires understanding the different operational characteristics of the intended traffic. The authors performed analyses using dispatch simulation

software to determine the impacts and causes of heterogeneity with freight and passenger traffic. The scenarios involved varying combinations of three different types of freight train and one passenger train. The train characteristics of speed, power-to-ton ratio, and priority were considered for their effect on delay and capacity, with priority appearing to have the greatest effect. Each contributed differently to train type heterogeneity, and future work will consider the magnitude of each of these factors in more detail.

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